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Evolution of the Colour–Radius Relation and the Morphology–Radius Relation in the SDSS Galaxy Clusters

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ABSTRACT

We have investigated the redshift evolution of the colour–cluster-centric-radius relation and the morphology–cluster-centric-radius relation in three redshift bins, $0.02 \leqslant z \leqslant 0.14$, $0.14 < z \leqslant 0.20$, and $0.20 < z \leqslant 0.30$ using a homogeneous sample of 736 galaxy clusters selected from the Sloan Digital Sky Survey. Both the relations are well-defined in all the redshift bins; the fraction of blue/late-type galaxies increases toward outside of clusters. Blue/late-type galaxy fractions are found to decrease with decreasing redshift at any cluster-centric radius. The trend is consistent with the Butcher-Oemler effect and the morphological Butcher-Oemler effect. In addition, we find that colour (spectral) evolution is almost completed by $z \sim 0.2$, whereas morphological evolution continues to the present day. The colour-radius relation is smooth in all the redshift bins, while the morphology–radius relation has a break only in the highest redshift bin. It is also found that fractions of blue-late type galaxies decreases mostly between the highest and the intermediate redshift bins, while fractions of red-late type galaxies continuously decreases with decreasing redshift through all the redshift bins. These results are consistent with the interpretation that the timescale of the colour (spectral) evolution is shorter than that of the morphological evolution. It is suggested that red-late type galaxies in the middle of the transformation are observed as passive spiral galaxies.

Key words: galaxies: clusters: general

1 INTRODUCTION

It is a remarkable feature of galaxy population that there exists a correlation between galaxy type-mix and environment. The correlation between morphology and environment has been studied by many authors (Dressler 1980; Postman & Geller 1984; Whitmore et al. 1993; Whitmore 1995; Dressler et al. 1997; Hashimoto & Oemler 1999; Fasano et al. 2000; Tran et al. 2001; Domínguez et al. 2001, 2002; Helsdon & Ponman 2003; Treu et al. 2003; Goto et al. 2003e). There is also a correlation between colours (spectra) and environment. It is known that the fractions of blue galaxies increases toward outer parts of clusters (e.g., Butcher & Oemler 1984; Rakos & Schombert 1995; Margoniner & de Carvalho 2000; but see Andreon et al. 2003).

Various physical mechanisms have been proposed to explain the correlations. Possible mechanisms include ram-pressure stripping of gas (Gunn & Gott 1972; Farouki & Shapiro 1980; Kent 1981; Fujita & Nagashima 1999; Abadi, Moore & Bower 1999; Quilis, Moore & Bower 2000); galaxy harassment via high speed impulsive encounters (Moore et al. 1996, 1999; Fujita 1998); cluster tidal forces (Byrd & Valtonen 1990; Valluri 1993; Fujita 1998; Gnedin 2003a,b) which distort galaxies as they come close to the centre; interaction/merging of galaxies (Icke 1985; Lavery & Henry 1988; Mamon 1992; Makino & Hut 1997; Bekki 1998; Finoguenov et al. 2003a); evaporation of the cold gas in disc galaxies via heat conduction from the surrounding hot ICM (Cowie & Songaila 1977; Fujita 2003); and a gradual decline in the SFR of a galaxy due to the stripping of halo gas (strangulation or suffocation; Larson, Tinsley & Caldwell 1980; Bekki et al. 2002; Kodama et al. 2001; Finoguenov et al. 2003b). Although these processes are all plausible, however, there exists little evidence demonstrating that any one of these processes is actually responsible for driving galaxy evolution.

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Since most of these processes act over an extended period of time, observations at a certain redshift cannot easily provide the detailed information that is needed to elucidate subtle and complicated cluster-related processes. It is worth noting that E+A (k+a or post-starburst) galaxies, which often thought to be cluster-related, are found to have their origin in merger/interaction with accompanying galaxies (Goto et al. 2003c,d), and thus E+A galaxies are not likely to be a product of the morphological transition in cluster regions.

To shed light on the underlying physical mechanisms, it is important to trace the redshift evolution of correlations among morphology, colour and environment. Studies on the evolution of morphology–density relation were attempted by Dressler et al. (1997) and Fasano et al. (2000), who reported the significant decrease in S0/E ratio toward increasing redshift up to $z \sim 0.4$. However, such studies were hampered by the inherent difficulty due to small and inhomogeneous cluster samples (e.g., Andreon 1998). They compared many nearby *poor* clusters observed with ground-based telescopes with the 10 *rich* clusters at high redshift observed with the Hubble Space Telescopes. On the colour evolution of cluster galaxies, it has been known that the fractions of blue galaxies in a cluster increases toward higher redshift (the Butcher–Oemler effect; Butcher & Oemler 1978,1984; Rakos & Schombert 1995; Margoniner & de Carvalho 2000; Margoniner et al. 2001; Goto et al. 2003a). To extract more information, it is important to investigate the mutual relationship between the correlations among colour, morphology, and environments.

With the advent of the Sloan Digital Sky Survey (SDSS; Stoughton et al. 2002), we now have a chance to step forward. One of the largest cluster catalogs with a well defined selection function is compiled from the SDSS (Goto et al. 2002a,b). In addition to the availability of the five optical colours in the SDSS (u, g, r, i, and z; Fukugita et al. 1996), this catalog has an advantage in that both high and low redshift clusters are detected using the same cluster finding algorithm (Goto et al. 2002a). In this study, we adopt the cluster-centric-radius as a parameter of environment, and investigate the evolution of colour–radius relation and morphology–radius relation.

The paper is organized as follows: In Section 2, we describe the SDSS data we used. In Section 3, we explain automated morphological classifications and the method to estimate type fraction. In Section 4, we present the results and discuss the physical implications. The cosmological parameters adopted throughout this paper are H_0=75 km s^{-1} Mpc^{-1}, and (Ω_m,Ω_Λ,Ω_k)=(0.3,0.7,0.0).

2 THE SDSS DATA

The data used in this study are essentially the same data as used in Goto et al. (2003a). The galaxy catalog is taken from the Sloan Digital Sky Survey Early Data Release (SDSS EDR; Stoughton et al. 2002), which covers ∼394 deg^2 of the sky (see Fukugita et al. 1996; Gunn et al. 1998; Lupton et al. 1999,2001,2002; York et al. 2000; Eisenstein et al. 2001; Hogg et al. 2001; Blanton et al. 2003; Richards et al. 2002; Stoughton et al. 2002; Strauss et al. 2002; Smith et al. 2002; Pier et al. 2003 for more detail of the SDSS data). The cluster catalog is presented in Goto et al. (2002a). In this study, we limit our sample clusters to those with richness between 20 and 80, using the cluster richness measured as a number of galaxies between $M_{r^*} = -24.0$ and -19.44 within 0.7 Mpc from a cluster centre after fore/background subtraction (see Goto et al. 2002b). These richness cuts nicely select rich clusters that allows us to study radial profile, and at the same time to reject richest clusters minimizing a possible richness related bias. The resulting number of clusters in our sample is still large ($N = 736$). We separate these clusters in three redshift bins; $0.02 \leqslant z \leqslant 0.14$, $0.14 < z \leqslant 0.20$, and $0.20 < z \leqslant 0.30$ (corresponding lookback time of 0.9, 1.9 and 2.7 Gyr). Each redshift bin has 82, 188 and 466 clusters, respectively.

3 ANALYSIS

In order to measure blue/late-type fractions, we have to subtract fore/background galaxy counts statistically since our galaxy catalog is based on the imaging data. The adopted procedure is the same to the one used in Goto et al. (2003a) except the use of global galaxy number counts. Instead of local galaxy number counts, we use the entire 394 deg^2 of the imaging data to calculate an average galaxy number counts in the magnitude range between $M_{r^*} = -24.0$ and -20.7. The use of global fore/background estimation is essential to probe slight over-densities in cluster perimeter regions. Among the entire region, cluster regions are only 2.4% in angular area. We re-scale this average galaxy number counts to meet an angular area of each radial bin, then subtract fore/background galaxy counts statistically.

Since a physical size of a cluster differs cluster by cluster, it is important to normalize the cluster radius when measuring blue/late type fractions. Since it is difficult to measure a virial radius using the imaging data, we measure a pseudo-virial radius in a following way to normalize the cluster-centric radius (see Goto et al. 2003a for details).

$$R_{vir} = 0.7 \times (Richness/32)^{1/3} (Mpc) \quad (1)$$

Equation (1) returns us with a normalized cluster radius of $R_{vir} = 0.7$ Mpc for clusters with $Richness = 32$ (c.f., 0.7 Mpc $\simeq$ a virial radius of a system with $\sigma = 350$ km s^{-1}). We note that R_{vir} is a pseudo-virial radius, and that caution is needed when comparing with a virial radius from a more realistic measurement such as velocity dispersion or X-ray radial profile. Using a position of the brightest cluster galaxy given in Goto et al. (2002a) as a cluster centre, we sum the number of blue/late and all galaxies within radial bins separated at $R_{cc}/R_{vir} = 0.2, 0.4, 0.7$ and 1.0 (R_{cc} is a distance from a cluster centre.), and then subtract fore/background statistically to measure blue/late-type fractions.

To classify galaxies into blue/late-type and others, we use exactly the same method as in Goto et al. (2003a), which we briefly summarize below. We use galaxies between $M_{r^*} = -24.0$ and -20.7. This absolute magnitude range assures the proper measurement of $u-r$ and $g-r$ colours for the faintest galaxies at the highest redshift bin. Fractions of blue galaxies are defined in two different ways; f_b and $f_{u-r<2.2}$. The first method, f_b, uses restframe $g-r$ colour. If a galaxy is bluer by more than 0.2 in $g-r$ than the colour of the red-sequence of elliptical galaxies at the redshift of the cluster, we define the galaxy as blue. This definition is a similar definition as

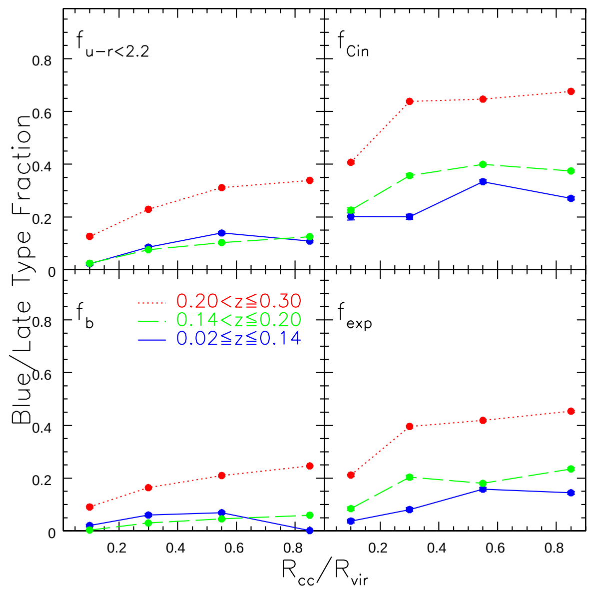

Figure 1. Evolution of the morphology/colour–radius relation. The fractions of blue/late-type galaxies are plotted against cluster-centric-radius normalized using cluster richness. The solid, dashed and dotted lines represent clusters with $0.02 \leqslant z \leqslant 0.14$, $0.14 < z \leqslant 0.20$, and $0.20 < z \leqslant 0.30$.

was used in original Butcher & Oemler (1984) and recently in Margoniner et al. (2001). The fraction of blue galaxy, f_b, is defined as the ratio of a number of blue galaxies to that of all galaxies after the global fore/background subtraction. The second method, $f_{u-r<2.2}$, defines a blue galaxy as a galaxy with $u - r < 2.2$ (Strateva et al. 2001). Again, the fraction of blue galaxy, $f_{u-r<2.2}$, is defined as the ratio of a number of blue galaxies to that of all galaxies after the global fore/background subtraction.

To separate galaxies into early/late-type morphologically, we use two different purely morphological parameters as are used in Goto et al. (2003a). The first one, f_{Cin}, uses a concentration parameter, Cin, defined as the ratio of Petrosian 50% flux radius to Petrosian 90% flux radius. We regard a galaxy with $Cin > 0.4$ as late-type (Shimasaku et al. 2001). Note that f_{Cin} can be affected by the seeing size. Goto et al. (2003a) estimated that an increasing seeing size might increase late-type fractions by ∼5% between $z = 0.3$ and $z = 0.02$. The other morphological classification, f_{exp}, uses galaxy radial profile fitting. When an exponential profile fits better than de Vaucouleurs' profile to a galaxy, the galaxy is classified into late-type. The fraction of late-type galaxy (f_{Cin} or f_{exp}) is defined as the ratio of a number of late-type galaxies to that of all galaxies after the global fore/background subtraction.

The errors on blue/late-type fractions are computed based on equation (2) of Goto et al. (2003a). The errors are as small as the dot size in Figure 1. Note that these errors do not consider errors in classifying galaxies into subcategories.

4 RESULTS & DISCUSSION

We present the evolution of the colour–radius relation and the morphology–radius relation based on the SDSS data in Figure 1, where blue/late type fractions are plotted against the normalized cluster-centric-radius for the three redshift bins. We use four annulus bins for radial direction (each separated at $R_{cc}/R_{vir} = 0.2, 0.4, 0.7$ and 1.0) and three redshift bins ($0.02 \leqslant z \leqslant 0.14$, $0.14 < z \leqslant 0.20$, and $0.20 < z \leqslant 0.30$). The $f_b, f_{u-r<2.2}, f_{Cin}$, and f_{exp} are plotted in the lower left, upper left, upper right, and lower right panels, respectively; i.e., the two left panels probe colour evolution of cluster galaxies and the two right panels are for morphological evolution. The following observational results can be recognized from Figure 1.

In all the panels, the fractions of blue/late type galaxies decrease with decreasing redshift at almost all cluster-centric-radius. The decrease is consistent with the Butcher–Oemler effect (left panels) and the morphological Butcher–Oemler effect (right panels).

The amount of decrease in fractions might be smaller for colour evolution (left panels; e.g., less than 20% decrease between the highest and the lowest redshift bins) than for morphological evolution (right panels; greater than 30% decrease between the highest and the lowest redshift bins). If the trend is real, it might imply that some red, late-type galaxies changed their morphology into early-type between $z = 0.3$ and $z = 0.02$.

Furthermore, at the intermediate redshift ($0.14 < z \leqslant 0.20$), the fractions of blue galaxies in the two left panels are almost as low as those at the lowest redshift bin ($0.02 \leqslant z \leqslant 0.14$). On the other hand, morphological late-type fractions shown in the two right panels are ∼10% larger than those at the lowest redshift bin. The trend might sug-

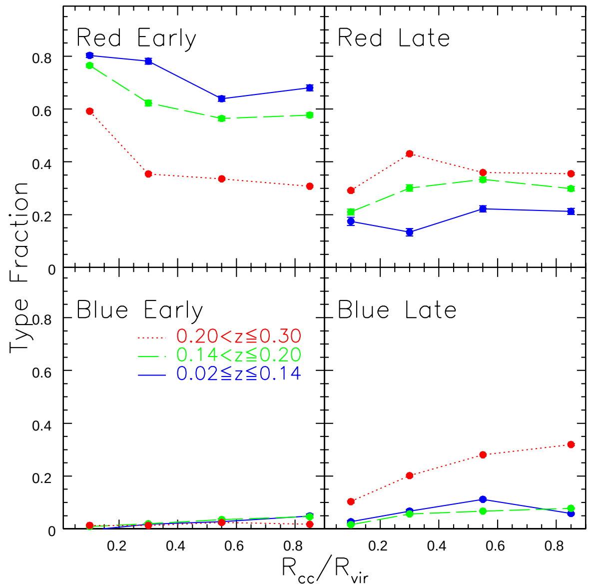

Figure 2. The fractions of four types of galaxies are plotted against cluster-centric-radius normalized using cluster richness. The criterion to separate red/blue is $u - r = 2.2$, and that for early/late is $Cin = 0.4$. The solid, dashed and dotted lines represent clusters with $0.02 \leqslant z \leqslant 0.14$, $0.14 < z \leqslant 0.20$, and $0.20 < z \leqslant 0.30$.

gest that the colour (spectral) evolution is already completed at the intermediate redshift bin, while the morphological evolution continues to the lowest redshift bin; i.e., timescale of the colour (spectral) evolution may be shorter than the timescale of the morphological evolution.

The radial profile are smooth for the fractions of blue galaxies at any redshift bin. However, for late-type fractions in the two right panels, the radial profiles seem to have a break at $R_{cc}/R_{vir} \sim 0.3$ at the highest redshift bin. Then, the profiles become smoother with decreasing redshift. A similar trend is found by Treu et al. (see their Fig. 17) in comparing the morphology–density relation of their cluster Cl0024+16 with that of the nearby cluster sample in Dressler (1980). The result indicates that the delayed morphological evolution occurs around $R_{cc}/R_{vir} = 0.3$–0.8, where many spectrally evolved, but morphologically unevolved galaxies possibly exist. The interpretation is consistent with Goto et al. (2003b), who found passive spiral galaxies in the infalling region (perimeter) of clusters. Note that Goto et al. (2003b) used galaxies with spectroscopy whereas this work statistically determines galaxy fractions from the imaging data (see also Couch et al. 1998; Poggianti et al. 1999 for passive spirals).

The difference in timescale of the spectral evolution and the morphological evolution is further clarified in Figure 2, where we plot fractions of four different types of galaxies as a function of cluster-centric-radius. Here, we classified galaxies into the following four different subsamples: blue-late ($u - r < 2.2$, $Cin \geqslant 0.4$), blue-early ($u - r < 2.2$, $Cin \geqslant 0.4$), red-late ($u - r \geqslant 2.2$, $Cin < 0.4$), and red-early ($u - r \geqslant 2.2$, $Cin < 0.4$). In the lower right and upper left panels, we plot the redshift evolution of blue-late and red-early types of galaxies as a function of cluster-centric-radius. As expected, red-early type shows gradual increase with decreasing redshift and blue-late type shows gradual decrease with decreasing redshift. However, a contrasting result is found when we compare red-late fractions (upper right) with blue-late fractions (lower right). The fractions of red-late type are not very much dependent on the cluster-centric-radius. In addition, red-late fractions show much evolution between the lowest and the intermediate redshift bins, whereas blue-late fractions show large evolution only between the highest and intermediate redshift bins. Assuming that blue galaxies evolve into red, and that late type evolves into early type, these results suggest that colour evolution (blue to red) mainly occurs between the highest and intermediate redshift, and that morphological evolution (late to early) continues toward the lowest redshift even after colour evolution was completed. In other words, it might indicate that morphological evolution needs longer timescale to be completed (∼2 Gyr) than the colour evolution does (∼1 Gyr). These estimates will provide a good benchmark to compare with semi-analytic simulations (e.g., Okamoto & Nagashima 2001; Diaferio et al. 2001; Benson et al. 2001; Springel et al. 2001; Okamoto & Nagashima 2003). Finally, we would like to mention that red-late type galaxies may be the same galaxy population as passive spiral galaxies found in Goto et al. (2003b).

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